Voltage Stability Analysis of a 16-bus Distribution Network Based on Voltage Sensitivity Factor

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Abstract—**Instability in a power system may be manifested in many different ways depending on the system configuration and operating mode. Voltage instability in power distribution systems could lead to voltage collapse and thus power blackouts. It is required to know the strength of the buses to improve the stability of the system. This paper analyzes and discusses the performance of static voltage stability of a 16 bus test system by varying the loadability with different sensitivities of distributed generation (DG). The synchronous generator, asynchronous generator and fuel cell are included in DG system. The performance analysis has been done by the simulation works using the DIgSILENT Power Factory 14.0. The analysis indicates a negative value of sensitivity with the increasing active power when using the asynchronous generator in various positions. The strength of different buses have been determined throughout the simulation according to the value of sensitivity and found that bus 7 is the weakest bus and bus 8 is the strongest bus. The increase in active power causes a decrease in loadability using asynchronous generator which shows no convergence in load flow after a certain value which means that the voltage is collapsed. So the placement of asynchronous generator in this test system is found inappropriate due to have lacking of reactive power.**

Keywords– **Voltage Stability, Distributed Generation, Voltage Sensitivity Factor and Loadability**

I. INTRODUCTION

Power system stability can be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to disturbance [1]**.** The importance of Distributed generation is getting more importance day by day. It works as a source of active power [2]. The location of distributed generation is another important factor to analyze stability of DG system [3].

The distribution network flows power in a unidirectional path where no little redundancy is found [4]. The resistance in the distribution line is the reason of having significant proportion of the voltage drop line losses and also the distribution lines [5]. Distribution generation plays the role of a small electric power generator or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and which is located close to the load [6]. Usually distributed generation means kind of small generation that provides nearly 30MW or less. In order to meet the customer needs and to provide an efficient operation of the distribution grid, it is sited at or near customer sites [7].

According to the demand of electricity supply, the distribution generation technologies are supplied to the customers. The advantageous side of DG is that, it gives market participants the chance to make response according to the market conditions which is changing with the variation of time. Moreover the small sizes and short construction lead times compared to most types central power plants make DG system more attractive [3]. Moreover, it provides flexibility in price, reliability and quality with the advantage of serving as a substitute of grid investments. The emission from DG technology is less than the coal power stations which proves that it is also environmentally friendly [8].

Unfortunately, the DG system could influence power quality problems, degradation in system reliability, reduction in the efficiency, over voltages and safety issues. The integration of distributed resources (DR) could influence the power quality due to poor voltage regulation, voltage flickers and harmonics. These conditions can have a serious impact on the operation and integrity of the electric power system as well as cause damaging conditions to equipment [8]. Thus, the improvement of DG stability is required by finding out the different strength level of different locations or buses.

The advantageous side of distributed resources (DR) is the reduction in transmission and distribution (T&D) losses, enhanced service reliability and quality, improved voltage regulation, relieved T&D system congestion [9]. This paper represents the performance of the DG's on the voltage stability of distribution network in terms of voltage sensitivity factor. So different sorts of DG system have been placed in various position of the distribution network and the bus strength have been determined individually. The change in voltage with the change in active power can determine the sensitivity that measures which bus will be unstable first so that necessary precautions can be taken. Moreover, the increase in active power increases the loadability for the synchronous generator and Photovoltaic cell (PV) but decrease the loadability after a certain period.

II. STATIC ANALYSIS OF VOLTAGE STABILITY

DGs contribute a lot in order to have progressive effect in system voltage stability. The research on the voltage stability can be classified into static and dynamic analysis [10]. Creating a lot of interruptions is the main reason to choose static voltage stability analysis rather than the dynamic one. The dynamic analysis dealt with non-linear load which makes them difficult to represent in a model form. Static voltage stability analysis is conducted by assuming the system is operating in the steady state [11]. Static load models are relevant to load flow studies as these express active and reactive powers as functions of the bus voltages. In general, a static load model that represents the power relationship to voltage can be expressed by the exponential equations:

$$P = Po\left(\frac{V}{Vo}\right)^{np} \quad (1)$$

$$Q = Qo\left(\frac{V}{Vo}\right)^{nq} \quad (2)$$

The parameters of this model are np, nq and the values of the active and reactive powers, $\boldsymbol{Po}$ and $\boldsymbol{Qo}$ at the unity voltage conditions. Starting from the current operating point of a transmission/distribution system, the condition of voltage stability is generally evaluated by means of the following three steps: i) define a proper voltage stability index to be assigned to all the load nodes; ii) identify through this index the weakest node, namely the first of all load nodes where voltage instability phenomenon can occur bringing the whole system to the voltage collapse; iii) evaluate the maximum loading capability of the entire system or of the weakest node, beyond which voltage collapse takes place [12]. Timely corrective actions can be taken only if an advance warning is issued to the system operator based on the measured stability indices.

III. VOLTAGE SENSITIVITY FACTOR

Voltage Sensitivity Factor (VSF) is an important parameter to find out the ranking of different bus strength [17]. When VSF (sensitivity factor) becomes large then it gives an indication that the system voltage is collapsed. By changing system loading, voltage sensitivity factor (VSF) can be calculated as:

$$VSF = \left\|\frac{dV}{dP}\right\| \quad (3)$$

The bus is said to be a weak bus if smaller changes in loading causes higher changes in sensitivity with the changes of voltage magnitude [13].

IV. NEWTON RAPHSON METHOD IN LOAD FLOW CALCULATION

The power flow programs use the power equation form with polar coordinates for any node k,

$$\tilde{S}_K = P_K + jQ_K = \tilde{V}_K \tilde{I}_K^* \quad (4)$$

Where, P_k and Q_k stands for real and reactive power respectively at node, k. The ultimate solution following the Newton Raphson application is found by the following equation:

$$[J]\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} = \begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (5)$$

Therefore, the expected small changes in voltage, V and angle Θ for small changes of Q and P can be computed. The Jacobian provides very useful information regarding voltage stability [1]. The critical power for different types of load model can be found using the value of jacobian, J.
The value of diagonal elements of the load flow Jacobian matrix reduces with the increase in load at a load bus. Voltage stability indices are based on this fact. This reduction is quite considerable as the voltage collapse point is approached. Voltage stability limit point in a power system gives a zero value of the jacobian matrix**.** Voltage collapse is a local phenomenon and is generally studied in terms of how much load at a particular bus can be increased before collapse of voltage occurs at this bus [14].

V. LOADABILITY FACTOR AS STABILITY INDEX

The single line system represents the following Fig. 1:

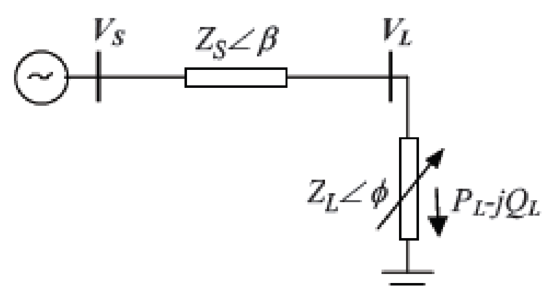

Fig. 1. Single line system [12]

If the impedance is $Z_L\angle\phi$ where V_s is the constant voltage source and I_L is the load current. The figure follows the equation:

$$\frac{V_S - V_L}{R + jX} = \frac{P_L - jQ_L}{V_L^*} \quad (6)$$

The following equation of load voltage magnitude can be given as:

$$V_L^4 - [V_s^2 - 2(RP_L + XQ_L)]V_L^2 + (R^2 + X^2)(P_L^2 + Q_L^2) = 0 \quad (7)$$

The following condition is valid only for two real and positive solutions which represents the stable state (A) and unstable state (B) assuming the load factor as constant where the system voltage will collapse if power P_X will increase beyond critical point, C.

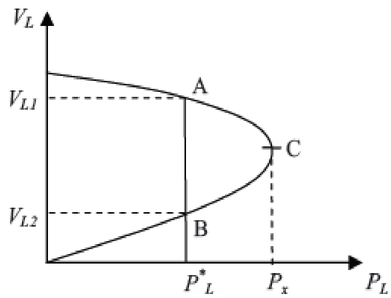

Fig. 2. PV curve [12]

The ratio of maximum apparent power of load to the nominal value is known as maximum loadability factor, f_{cx}.By using (3) & solving with respect to f_{cx} we obtain:

$$f_{cx} = V_S^2 \left[\frac{-RP_L - XQ_L + \sqrt{(R^2+X^2)(P_L^2+Q_L^2)}}{2(XP_L - RQ_L)^2} \right] \quad (8)$$

Also the stability index (SI) using (3) is found to be:

$$SI^1 = V_S^4 4V_S^2(RP_L + XQ_L)] - 4(XP_L - RQ_L)^2 \quad (9)$$

The system will be more stable if the SI will be more than zero [11].

VI. TYPES OF DISTRIBUTED GENERATION

Depending on the size, power time duration, construction, technology and other factors, the DGs are classified into different parts [15]. The DGs may also be grouped into four major types based on terminal characteristics in terms of real and reactive power delivering capability as described in (Hung *et al*, 2010). Four major types are considered for comparative studies which are described as follows:

Type1: This type DG is capable of delivering only active power such as photovoltaic, micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters. However, according to current situation and grid codes the photovoltaic can and in sometimes are required to provide reactive power as well.

Type2: DG capable of delivering both active and reactive power. DG units based on synchronous machines (cogeneration, gas turbine, etc.) come under this type

Type3 DG capable of delivering active power but consuming reactive power. Mainly induction generators, which are used in wind farms, come under this category. However, doubly fed induction generator (DFIG) systems may consume or produce reactive power.

Type4: DG capable of delivering only reactive power. Synchronous compensators such as gas turbines are the example of this type and operate at zero power factors. In this paper the impact of type 1, type 2 and type 3 generators are considered by increasing the active power level [15]. Different responses are found in different cases which are described in section VII.

VII. SIMULATION RESULTS AND ANALYSIS

This paper represents the performance of the DGs on the voltage stability of distribution network in terms of voltage sensitivity factor.

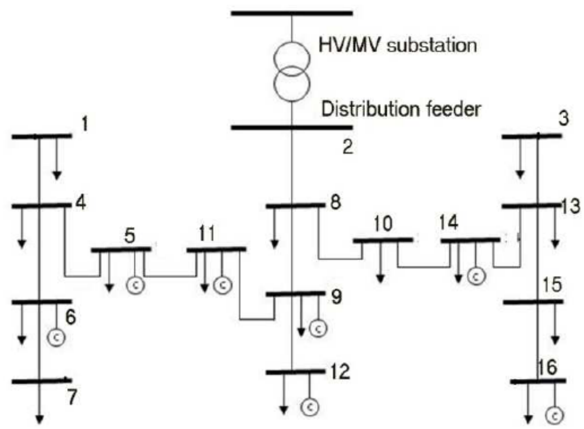

Fig. 3. Single line diagram of a 16 bus test system [13]

The analysis has been done with a modified form of a 16 bus standard distribution system used in [16]. The total loading of the distribution system is 28.7MW and it is basically a 23kV primary distribution system. The system has been shown in Fig. 3. Ranking of bus strength based on sensitivity in a 16 bus distribution system is found by the simulation with DIgSILENT PowerFactory 14.0 [17] which is basically a commercial tool. Different distributed generation systems (synchronous generator, asynchronous generator and PV cell) have been placed in the distribution system.

In this simulation work, synchronous generator is connected with increasing the active power in bus 1 and observed and record the sensitivity for all of the 16 buses. An asynchronous generator is connected in the place of synchronous generator with increasing the active power in bus 1 and observed and record the sensitivity for all of the 16 buses. Similar thing has been done for the PV cell. For all of the buses, the same sequence simulation work has been done.

Different buses from bus 1 to 16 responds in different ways with point of view of sensitivity as shown in Table I. The symbol "/" in Table-I indicates the voltage collapse. According to the value of sensitivity with the variation of loading in different buses, it is found that bus 7 and bus 8 is the weakest and strongest bus, respectively. The sensitivity response for bus 1 is neither so stronger nor so weak.

In case of asynchronous generator whenever the active power increases, the value of loadability decreases. The more the bus strength, the more it will calculate the load flow calculation. Bus 7 is the weakest bus which cannot calculate the load flow due to higher loading and hence the system voltage collapse.

Table I: Sensitivity measurement with active power, P_{asyn} variation for asynchronous generator

Active power, Pasyn (MW)	Sensitivity at Bus 1	Sensitivity at Bus 7	Sensitivityat Bus 8
3	0.0156	0.027016	0.001861
4	0.017904	-0.1	0.00185
5	-0.1137	-0.10429	0.001843
6	0.201416	-0.1	0.001842
9	0.014777	0.061303	0.002076
12	0.01465	/	0.001463
13	/	/	0.001685
13.5	/	/	-0.1
13.6	/	/	-0.0013
13.7	/	/	/

Lacking of reactive power shows the negative result in different buses in different loading period which results for negative value in sensitivity as shown in Fig. 4. The nature of bus 1,7,8 are indicated by different colours respectively which results for voltage fluctuation . Ultimately it shows that voltage is collapsed after a certain period of insertion of active power.

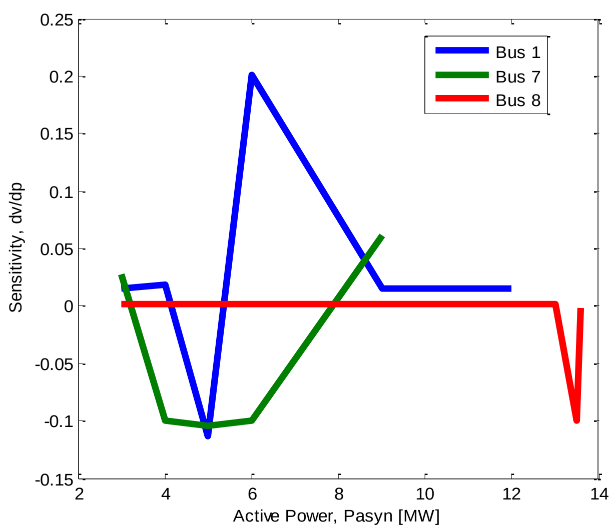

Fig. 4. Sensitivity Vs Active power for bus 1,7,8 using asynchronous generator

Table II: Sensitivity measurement with active power, P_{syn} variation for synchronous generator

Active power, Psyn (MW)	Sensitivity at Bus 1	Sensitivity at Bus 7	Sensitivity at Bus 8
3	0.013815	0.019645	0.001845
6	0.012694	0.017928	0.001831
9	0.011895	0.015853	0.001818
12	0.010794	0.014371	0.00176
15	0.009967	0.012696	0.001748
18	0.009331	0.010988	0.001738
21	0.008433	0.009672	0.001728
24	0.007709	0.008574	0.001676
27	0.007107	0.007347	0.001667
30	0.006596	0.006065	0.001659

The increase in active power using synchronous generator decrease the sensitivity which results for stable condition in the system. The ultimate overview is found by the following Fig. 5:

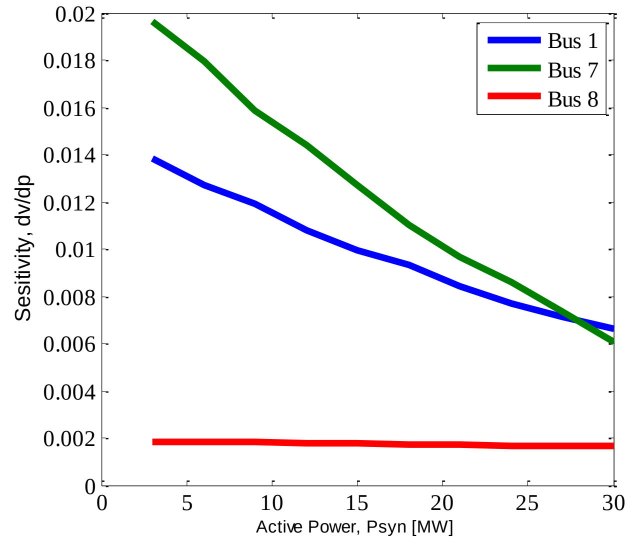

Fig. 5. Sensitivity Vs Active power for bus 1,7,8 using synchronous generator

Table III: Sensitivity measurement with active power variation, P for PV cell

Loading, P(MW)	Sensitivity at Bus 1	Sensitivity at Bus 7	Sensitivity at Bus8
3	0.013815	0.019635	0.001845
6	0.012699	0.017926	0.001831
9	0.011894	0.015851	0.001818
12	0.010793	0.014367	0.001766
15	0.009963	0.012696	0.001748
18	0.009331	0.010988	0.001738
21	0.008433	0.009672	0.001728
24	0.007709	0.008574	0.001676
27	0.007107	0.007347	0.001667
30	0.006595	0.006065	0.001659

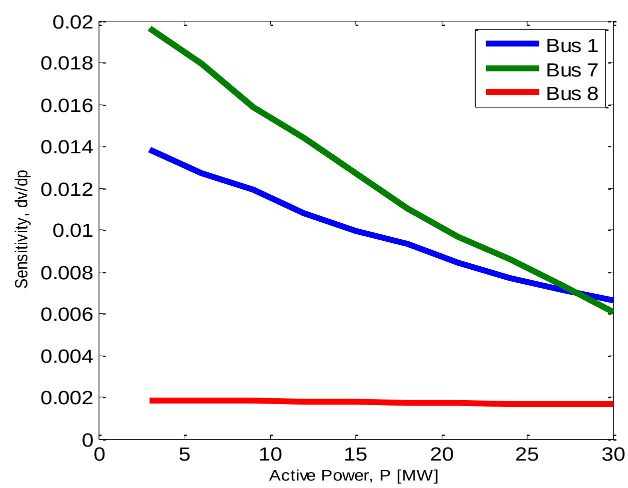

Fig. 6. Sensitivity Vs Active power for bus 1,7,8 using PV cell

The impact of synchronous generator and PV cell placing in different buses shows the simulation result found in Table II and Table III. The more the value of active power, the more the loadability is found to be increased and hence sensitivity decreases which is found for synchronous generator and PV cell. Using asynchronous generator in the system, variation of positive and negative sensitivity is found which is not the appropriate choice for the 16 bus test system. The repetitive load flow calculation indicates the value of the loadability limit also. It is ultimately found that changes in active power does not affect the synchronous generator and PV cell but the performance of asynchronous generator is degraded with the injection of active power.

Table IV: Loadability of Asynchronous generator (AG) and Synchronous generator (SG) with increasing power at bus 8

Active power, Pasyn (MW)	Load-ability of AG	Active power, Psyn(MW)	Load-ability of SG
9	3.31	9	4.07
12	1.32	12	4.18
13	0.958	15	4.49
14	No load flow	18	4.59

The simulation results for increasing active power gives a decreased loadability in asynchronous generator which results that the power is found to be operated far away from critical power point. It indicates that the system voltage is collapsed for the further insertion of active power where no load flow occurs. But the performance is found in opposite in the case of synchronous generator and PV cell where the loadability increases and the system is staying at the level of stable zone.

VIII. CONCLUSION

The load flow method has been applied in the modified 16 bus distribution system where different variation of sensitivity response is found for different loadability limit in different buses. The different type of distribution networks are found to be response in different manner which is reflected in the simulation and result part in point of view of loadability and sensitivity. Moreover, the difference in synchronous and the asynchronous results are comparable enough in showing different impact in the 16bus distribution system.

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